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Paleocurrent Analysis of the Cretaceous Mitchell Formation, North-Central Oregon

Craig A. Sandefur

ABSTRACT

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Mitchell Formation,
North-Central Oregon

by
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Cretaceous sedimentary rocks of north-central Oregon previously referred to as the Hudspeth and Gable Creek formations and recently renamed the Mitchell Formation are potential petroleum source and reservoir rocks. Thus, determining their extent under the cover of Tertiary volcanics is of great importance to future petroleum exploration in the southern half of the Columbia Basin. The direction of sediment transport has been previously studied by several workers with contradicting results and conclusions. The primary objective of this research was to expand the paleocurrent analysis using both macro- and micro-fabric to provide additional evidence of sediment transport direction. This information allows a better prediction of the extent, thickness, and petroleum potential of the marine Cretaceous rocks.

From field study of both sedimentary structures and gross lithology my work reconfirms that these sediments are part of a sub-sea fan complex consisting of fan-apron-facies

turbidites and mudstones (Hudspeth mudstone facies) and channel-facies conglomerates and sandstones (Gable Creek sandstone-conglomerate facies). Sole marks, flute casts, pebble imbrication, and alignment of plant fragments indicate that sediment transport was generally from south to north into a northeast-southwest elongate basin. These results suggest that the greatest potential for petroleum production from Cretaceous sediments in north-central Oregon lies in restricted rift-type basins such as those in the surrounding area of Mitchell.

LOMA LINDA UNIVERSITY

Graduate School

PALEOCURRENT ANALYSIS OF THE CRETACEOUS MITCHELL FORMATION, NORTH-CENTRAL OREGON

by

Craig A. Sandefur

A Thesis in Partial Fulfillment
of the Requirements for the Degree Master of Science
in Geology

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Each person whose signature appears below certifies that this thesis in his opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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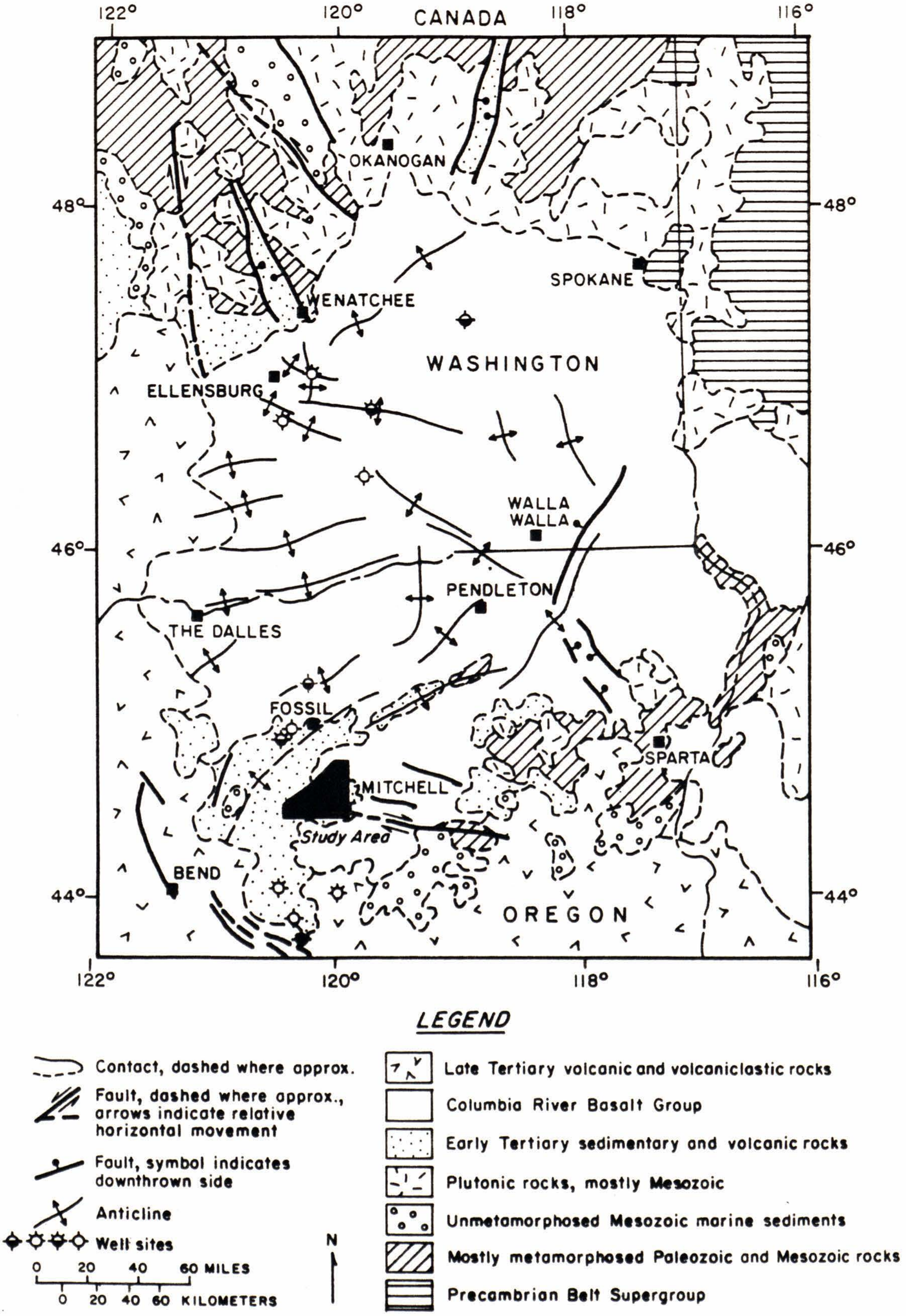
INTRODUCTION

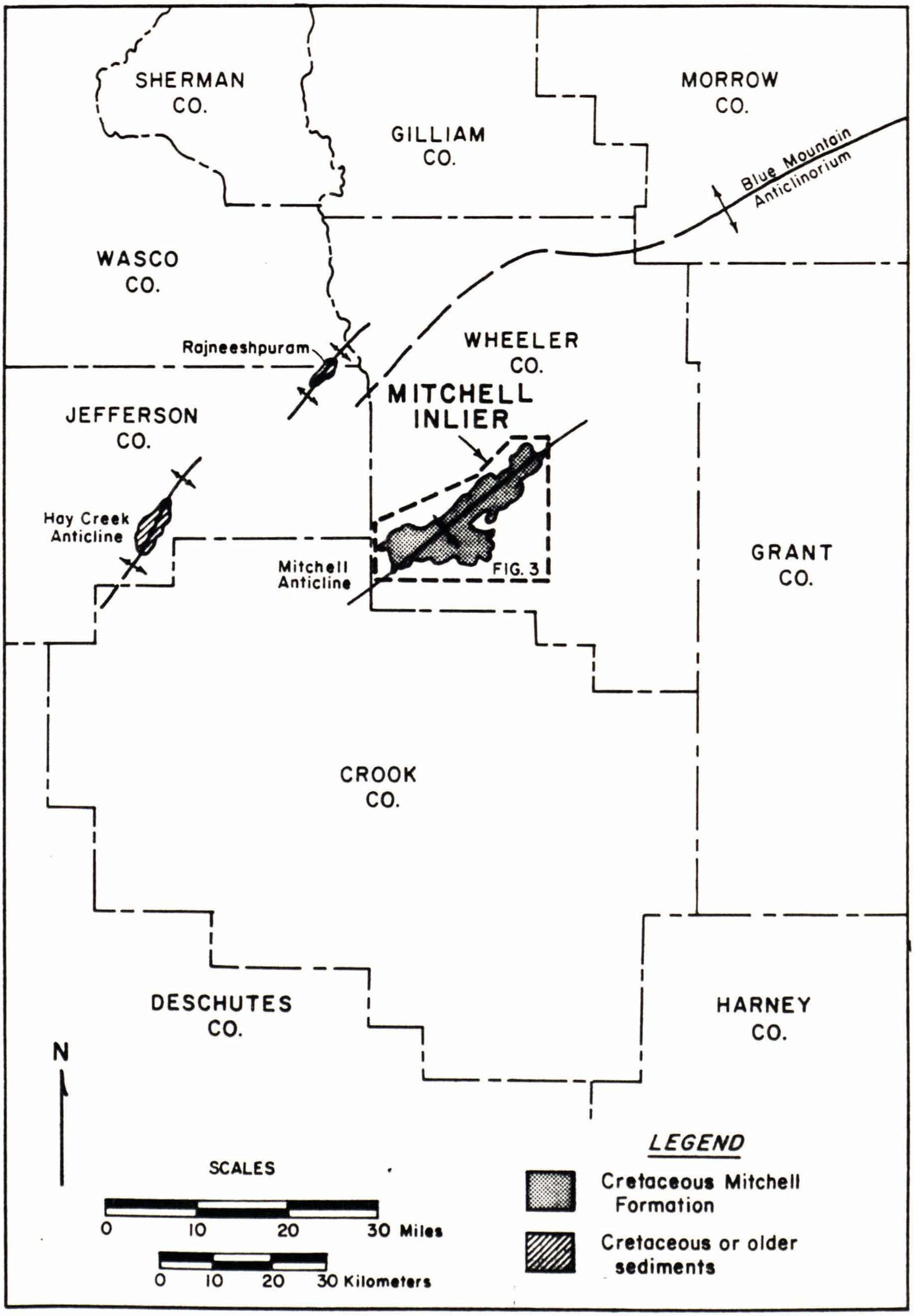
Although to date there has been no commercial hydrocarbon production in north-central Oregon, several major independent oil companies are convinced that the marine Cretaceous rocks in the area (Figure 1) have both source and reservoir rock potential and thus warrant serious exploration and further investigation. The petroleum potential of the area is greatest if these marine sediments are continuous and have a wide distribution under the cover of Tertiary volcanic rocks. However, accurately predicting their distribution, without the expense of drilling or the use of costly and, at current levels of technology, questionably useful seismic methods, requires that the depositional environment, the mode of deposition and specifically the direction of sediment transport be known. At present the geologic literature contains conflicting data and interpretations regarding these parameters.

Figure 1. Index map of the Columbia Basin with the study area in north-central Oregon outlined. [Modified from Kleinhans et al. (1984).]



122°
120°
CANADA
118°
116°
48°
46°
44°
OKANOGAN
WENATCHEE
SPOKANE
WASHINGTON
ELLENSBURG
WALLA WALLA
PENDLETON
THE DALLES
FOSSIL
SPARTA
MITCHELL
Study Area
BEND
OREGON
LEGEND
Contact, dashed where approx.
Fault, dashed where approx., arrows indicate relative horizontal movement
Fault, symbol indicates downthrown side
Anticline
Well sites
0 20 40 60 MILES
0 20 40 60 KILOMETERS
N
Late Tertiary volcanic and volcaniclastic rocks
Columbia River Basalt Group
Early Tertiary sedimentary and volcanic rocks
Plutonic rocks, mostly Mesozoic
Unmetamorphosed Mesozoic marine sediments
Mostly metamorphosed Paleozoic and Mesozoic rocks
Precambrian Belt Supergroup

Figure 2. Map showing the Mitchell Inlier. [Modified from Kleinhans et al.(1984).]


SHERMAN CO.
GILLIAM CO.
MORROW CO.
Blue Mountain Anticlinorium
WASCO CO.
Rajneeshpuram
WHEELER CO.
MITCHELL INLIER
JEFFERSON CO.
Hay Creek Anticline
Mitchell Anticline
FIG. 3
GRANT CO.
CROOK CO.
DESCHUTES CO.
HARNEY CO.
N
SCALES
0 10 20 30 Miles
0 10 20 30 Kilometers
LEGEND
Cretaceous Mitchell Formation
Cretaceous or older sediments

PURPOSE AND OBJECTIVES

This study was conducted for the purpose of further investigating in detail the paleocurrent directions exhibited by the Cretaceous sedimentary rocks of north-central Oregon, specifically those that outcrop in the Mitchell Inlier (Figure 2). The Cretaceous rocks outcrop along the eroded axis of the Mitchell Anticline and were formally separated on the basis of lithology into the Hudspeth and Gable Creek formations by Wilkinson and Oles (1968).

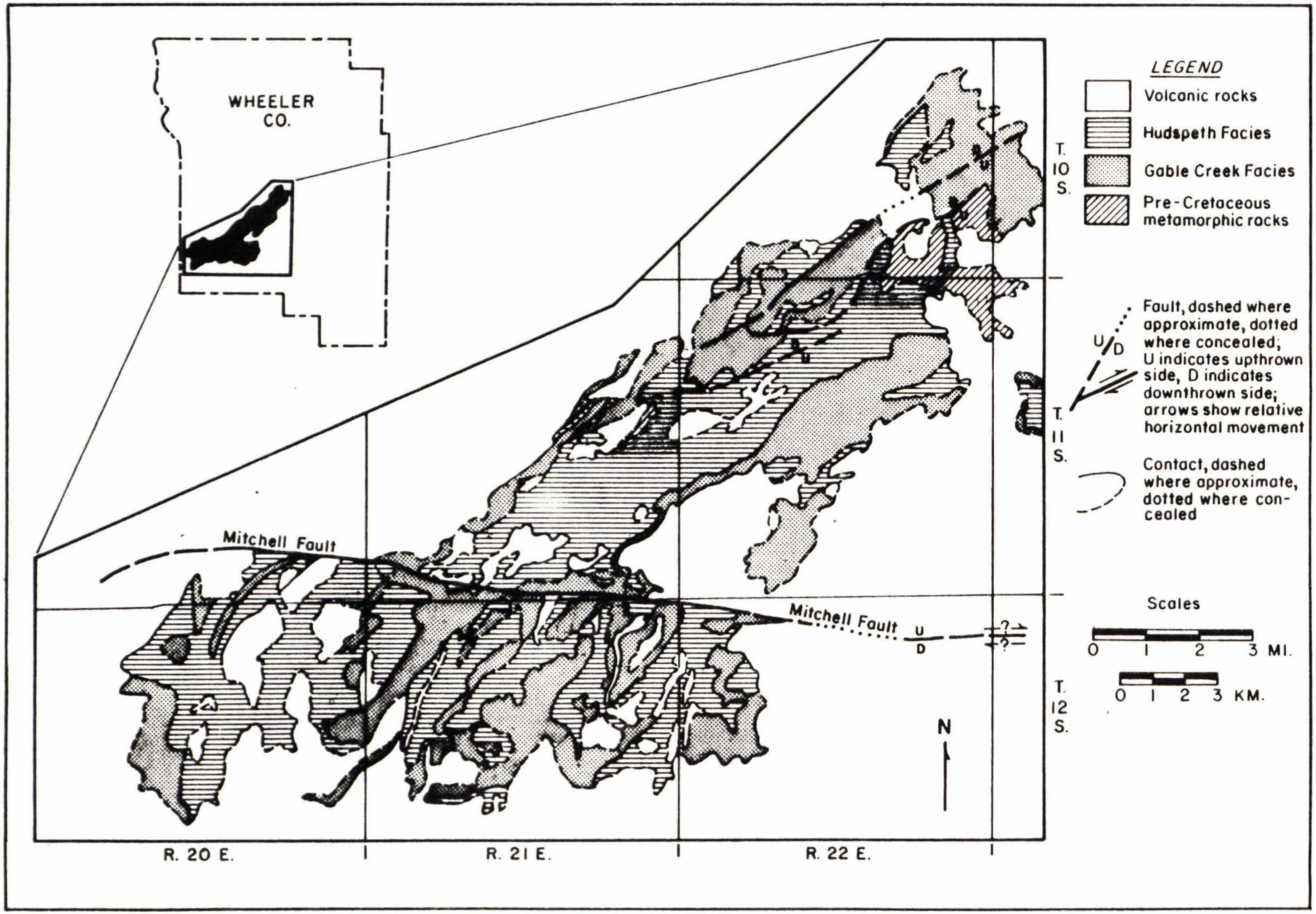
STRATIGRAPHY

History

The principal outcrops of Cretaceous rocks in north-central Oregon are found in an erosional window exposed in the Mitchell area (Figure 3) located in south central Wheeler County (Walker 1973 and 1977). The stratigraphy in this area has been worked out in detail by Merriam (1901), Swarbrick (1953), Bowers (1953), McIntyre (1953), Taylor (1960), McKnight (1964), Wilkinson and Oles (1968), Oles and Enlows (1971), Oles (1973), Enlows and Oles (1973), and Robinson (1973 and 1975).

Prior to being formally named and given stratigraphic rank by Wilkinson and Oles (1968) the Cretaceous rocks in the Mitchell area had been informally divided and named by several workers. The first published report on the Cretaceous rocks in the Mitchell area was in a California Geological Survey publication by W.M. Gabb in 1868. In 1871 Thomas Condon published a report on the area, and although the primary subject of the publication was the Tertiary history of the John Day Valley, he reported the presence of Cretaceous-aged rocks in the area. In 1871 Marsh requested that Condon lead a fossil collecting party into the region (Merriam 1901) and after a second visit to the area in 1873 published a brief report referring to the beds under-

Figure 3. Generalized geologic map of the Cretaceous rocks exposed in the Mitchell area. [(Modified from Kleinhans et al. (1984) after Wilkinson and Oles (1968).]


WHEELER
CO.
LEGEND
Volcanic rocks
Hudspeth Facies
Gable Creek Facies
Pre-Cretaceous metamorphic rocks
Fault, dashed where approximate, dotted where concealed; U indicates upthrown side, D indicates downthrown side; arrows show relative horizontal movement
Contact, dashed where approximate, dotted where concealed
U
D
Mitchell Fault
Mitchell Fault
T. 10 S.
T. 11 S.
T. 12 S.
R. 20 E.
R. 21 E.
R. 22 E.
Scales
0 1 2 3 MI.
0 1 2 3 KM.
N

lying the fossiliferous Tertiary sediments as Mesozoic and "apparently Cretaceous." In 1901 Merriam published the first report on the lithology of the Cretaceous rocks in the area. Packard in 1928 divided the unnamed Cretaceous rocks into four members, also unnamed. The lowermost member was composed of sandstone and shale which were overlain successively by a conglomerate member, a shale member, and another conglomerate member. All these early workers, including Chaney (1933), Hodge (1932, 1942), and Wilkinson (1959), were apparently comfortable referring to the Cretaceous rocks in the Mitchell area only informally as " the Cretaceous rocks of Central Oregon" or "the Cretaceous beds at Mitchell." As late as 1960 Popenoe et al. remarked on the lack of formal stratigraphic nomenclature.

The first attempts to name and rank the Mitchell area Cretaceous rocks were in three masters theses completed at Oregon State University (OSU) in 1953. Swarbrick's (1953) thesis was the first in a rapid sucession of three theses, completed on the area. Swarbrick informally named all the Cretaceous rocks in the Mitchell area the "Mitchell formation" subdividing it into two members: the "Black Butte shale member" consisting primarily of mudstone, siltstone, shale, and sandstone and the "West Branch conglomerate member" consisting of conglomerate and sandstone. Contemporaneous with Swarbrick's (1953) thesis were two OSU theses submitted by Bowers (1953) and McIntyre (1953). These theses also dealt informally with the stratigraphy of the Mitchell area. Bowers referred to the Cretaceous rocks as the "Mitchell beds" and recognized three sub-units. The lowermost unit, consisting primarily of coarse-grained sandstones and pebble conglomerates, he termed the "Basal Mitchell unit". The overlying sandstone-shale sequence Bowers (1953) named the "Frizzell shale unit". The uppermost unit, consisting of conglomerates with interbedded sandstones and shales, he named the "Frizzell conglomerate unit". McIntyre (1953) referred to the Cretaceous rocks in the Mitchell area as the "Mitchell group" and on the basis of lithologies divided it into three separate formations: the "Anderson shale" (roughly equivalent to the "Main Mudstone member" of Wilkinson and Oles 1968), the "Marshall Butte conglomerate" (equivalent to the Gable Creek Formation of Wilkinson and Oles 1968), and the "Keyes shale" (the equivalent of which is unclear). From the locality and descriptions given by McIntyre, the "Keyes shale" appears to represent a complex intertonguing of the Hudspeth and Gable Creek formations of Wilkinson and Oles (1968).

In a later OSU masters thesis, McKnight (1964) divided the Cretaceous stratigraphic sequence into two separate formations. He named the fine-grained rocks the "Meyers Formation" and the coarse-grained rocks the

"Frizzell Formation".

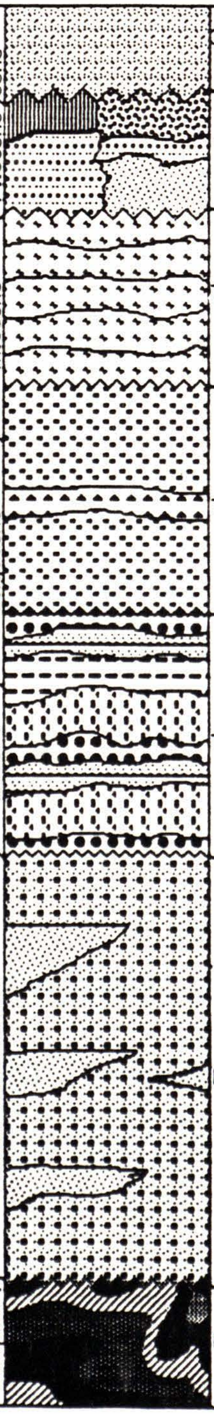
Four years later when Wilkinson and Oles (1968) formally named and described the Cretaceous rocks of the Mitchell Inlier , the OSU theses by McKnight (1964), Swarbrick (1953), Bowers (1953), and McIntyre (1953) were not specifically referenced. However, following McKnight's (1964) lithologic subdivision of the rock sequence, Wilkinson and Oles (1968) divided the Cretaceous into two separate formations, renaming the fine-grained portion the Hudspeth Formation and the coarse-grained portion the Gable Creek Formation.

New Nomenclature

In a separate publication Fisk and Sandefur (manuscript in preparation) point out that both the Hudspeth and Gable Creek originate from and are the direct result of the same sediment dispersal system. We propose for this reason that the Gable Creek and Hudspeth formations be relegated to the status of facies within the newly renamed Mitchell Formation (Figure 4).

The basal unit of the Mitchell Formation, composed of thin sandstone and conglomerate beds, lies with angular unconformity on Permo-Triassic metasediments. Although Wilkinson and Oles (1968) informally referred to this lowermost unit as the "Basal member" of the Hudspeth Formation,

Figure 4. Generalized stratigraphic column of north-central Oregon. [Modified from Oles and Enlows (1971).]



Quat.	Pleisto-cene	Qal	Vari-able	Quaternary deposits	Valley-fill and flood plain deposits.
Tertiary	Pliocene	Td	0'-800'	Dalles Group	Td: Volcanic sediments intertonguing basalt flows and ignimbrites.
	Miocene	Tcr	0'-3000'	Columbia River Basalt Group	Tcr: Thick basalts with tuffaceous interbeds
	? Oligocene	Tjd	0'-4000' ±	John Day Formation	Varicolored lacustrine tuffs, sandstones, ignimbrites and breccias.
	? Eocene	Tc	0'-6000' ±	Clarno Formation	Varicolored tuffs, mudflows, andesite flows and occasional breccias; some andesitic intrusions.
Cretaceous	Albian-Cenomanian	Km	9000' ±	Mitchell Formation	Coarse pebble conglomerates and sandstones of the Gable Creek facies intertonguing with mudstone and siltstones of the Hudspeth facies.
Permian	Wolf-campian ?	Pm	?	Metamorphics	Greenschists, blueschists, phyllites, marbles, with some quartzites and other metasediments.

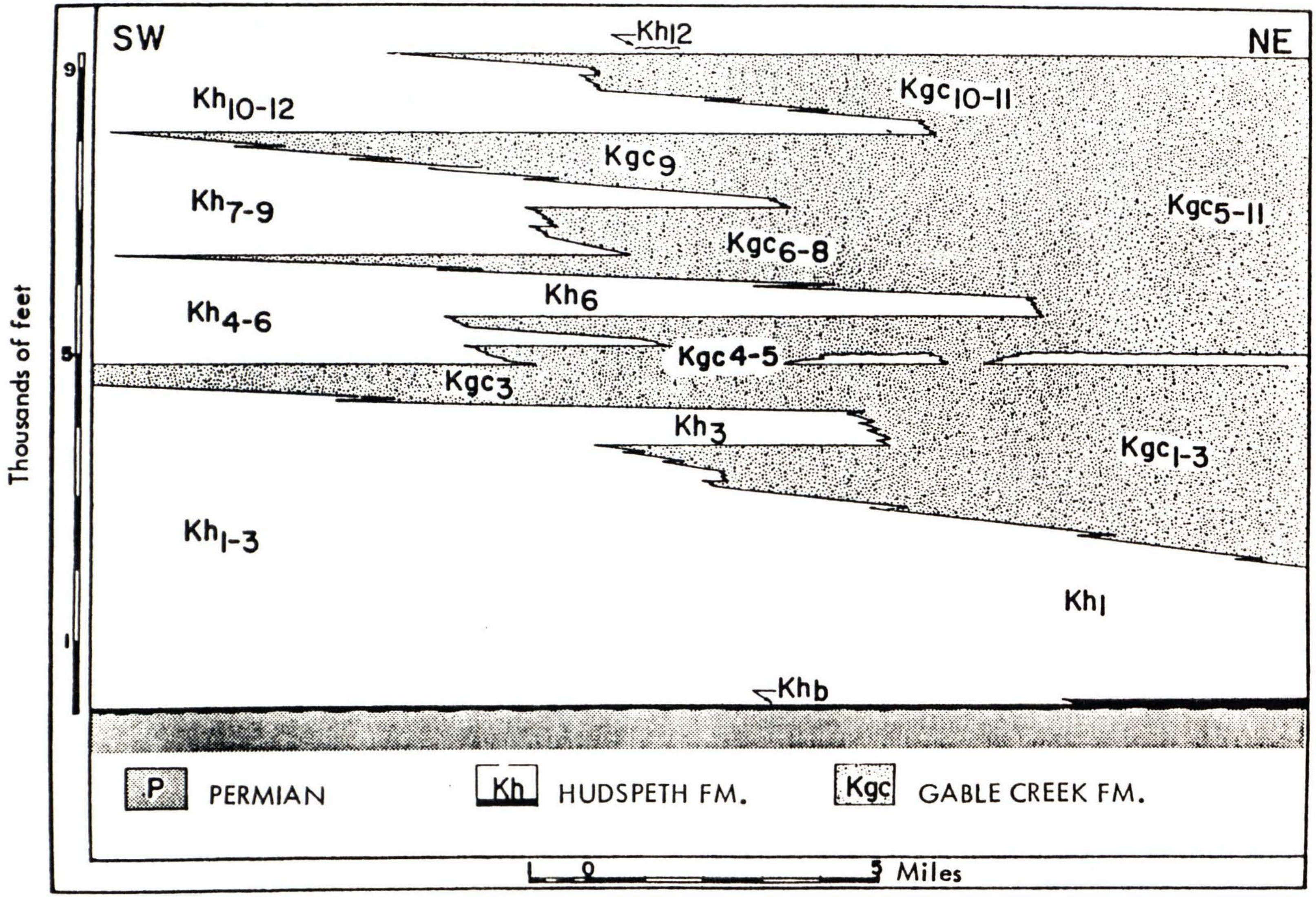
due to its coarse-grained nature we include it in the Gable Creek sandstone-conglomerate facies. However, because it is lithologically distinct (Jarman 1973 ; Dickinson et al. 1979) and may be older than the rest of the sequence (Kleinhans et al. 1984), further work may demonstrate the need to formally recognize this basal unit as either a separate member or formation.

Overlying the basal conglomerate is a thick mudstone and siltstone unit referred to the Hudspeth and informally termed the "Main Mudstone member" by Wilkinson and Oles (1968). Above this lies a sequence of eleven mudstone and eleven conglomerate-sandstone "tongues" (Wilkinson and Oles 1968). The former I refer to the Hudspeth mudstone facies and the latter to the Gable Creek sandstone-conglomerate facies (Figure 5).

Hudspeth Mudstone Facies

The Hudspeth mudstone facies as defined by Fisk and Sandefur (manuscript in preparation) consists primarily of mudstone and siltstone with minor beds of very fine- to coarse-grained sandstone (Figure 6). Thickness of the facies is exceedingly variable with a maximum thickness of 3000 feet reported by Wilkinson and Oles (1968). The Hudspeth has been generally described by McKnight (1964), Wilkinson and Oles (1968), and Jarman (1973) as gray in

Figure 5. Intertonguing relationship of the Gable Creek sandstone-conglomerate facies with the Hudspeth mudstone facies. [Modified from Oles (1973).]


SW
NE
Kh12
Kh10-12
Kgc10-11
Kgc9
Kh7-9
Kgc5-11
Kgc6-8
Kh6
Kh4-6
Kgc4-5
Kgc3
Kh3
Kgc1-3
Kh1-3
Kh1
Khb
Thousands of feet
9
5
1
P PERMIAN
Kh HUDSPETH FM.
Kgc GABLE CREEK FM.
0
5 Miles

color when fresh, weathering to a light gray, thin to thickly laminated, and composed of approximately fifty-five percent silt-size quartz, feldspar, chlorite, sericite, and mica. The matrix is composed of clays, chlorite, sericite, leucoxene, hematite, and chalcedonic silica (Jarman 1973). Carbonized plant fragments are abundant throughout the facies.

Gable Creek Sandstone-Conglomerate Facies

The Gable Creek sandstone-conglomerate facies as described by McKnight (1964) and Wilkinson and Oles (1968) consists of a series of very thickly-bedded to massive conglomerates and coarse sandstones with lenses of finer-grained sandstones and mudstones incorporated within it (Figure 7). Cherts and quartzite pebbles make up the majority of the clasts with subordinate amounts of granite and metamorphics also present (McKnight 1964). The clasts are rounded to subrounded, average one to two inches in diameter, but include cobbles and boulders (Wilkinson and Oles 1968). The interbedded mudstones are identical to those in the Hudspeth facies and are by definition part of it, although originally included within the Gable Creek Formation by Wilkinson and Oles (1968).

Figure 6. Outcrop of the Hudspeth mudstone facies of the Mitchell Formation exposed in roadcut along Highway 26 approximately 10 miles west of Mitchell.

Figure 7. Outcrop of Gable Creek sandstone-conglomerate facies of the Mitchell Formation approximately 10 miles west of Mitchell.

SEDIMENTOLOGY

Depositional Environment

Historically, there have been conflicting interpretations of the depositional environment of the Mitchell Formation. Swarbrick (1953) interpreted the fine-grained clastics to be deposited in a shallow marine environment but noted that "offshore currents and wave action had little effect on the sediments deposited as a whole." In 1964, McKnight interpreted the depositional environment as marine with evidence of high energy manifested by the presence of conglomerates interbedded with sandstones. The thick mudstones within the Hudspeth facies were interpreted by McKnight (1964) to be deposited in fairly deep water. The thin- to medium-bedded wacke sandstones often displaying solemarkings and graded bedding to him implied rapid deposition. McKnight (1964) also stated that "these are similar to occurrences of sandstone interpreted as turbidity current deposits by many authors." This prematurely perceptive interpretation went unacknowleged and was ignored in late publications.

Wilkinson and Oles (1968) interpreted the depositional environment to be a "large sheltered, shallow-marine embayment into which a major river poured clastic debris." The

Gable Creek facies was interpreted by Wilkinson and Oles (1968) as "a fluvial-deltaic conglomerate" formed by a swinging distributary emptying into this embayment. The intertonguing relationship of the Hudspeth marine mudstones with "fluvial-deltaic" conglomerates was explained by Wilkinson and Oles (1968) as having resulted from the interaction of three processes: the subsidence of the basin of deposition, intermittent uplift of the source area, and periodic reorientation of the major distributory channel of a large river. In her 1973 OSU dissertation on the Hudspeth, Jarman echoed Wilkinson and Oles' (1968) interpretation. Although many geologists have since informally reinterpreted the sediments as deposited in a deep-sea-fan environment, a formal paleoenvironmental reinterpretation was not published until 1984 when Kleinhans et al. convincingly reinterpreted the Cretaceous rocks of the Mitchell Inlier as deep-sea-fan deposits. This long overdue and much needed reinterpretation set the stage for my paleocurrent analysis.

Paleocurrent Direction

The transport direction of Hudspeth and Gable Creek sediments has previously been studied by several workers but with contradicting results and conclusions. The first author to deal with paleocurrent analysis of the area was

McKnight who in his 1964 OSU masters thesis concluded that the sediments were transported from a southeastern source area toward the north-northwest. In their 1968 paper Wilkinson and Oles presented the results of a limited paleocurrent study drawing conclusions directly opposite to those of McKnight (1964). Wilkinson and Oles proposed a paleocurrent direction generally from north to south, dismissing McKnight's data (without specifically referencing it) with the rather peculiar statement that "all data indicate that the paleoslope was inclined toward the south." Wilkinson and Oles used as directional indicators the inclination of cross beds and local imbricate structures. However, they provided only meager evidence to support their conclusions. Elsewhere in the same paper the authors conceded that, although multiple current flow directions were found, varying from west-northwest through south to east, the "vast majority define a transport direction which lay within the quadrant southwest to southeast" (Wilkinson and Oles 1968). In a doctoral dissertation completed at OSU in 1973, Jarman, using additional data from cross-bedding and ripple marks, restated Wilkinson and Oles' (1968) opinion of a prevailing current direction from north to south again in contradiction to the conclusions of McKnight (1964). Recently, Kleinhans et al. (1984) presented data from the lowermost portion of the Cretaceous section that indicate a northerly direction of transport. However, data presented from the upper portion of the section seems to indicate transport was in an easterly direction.

Thus there exists a major discrepancy in the results of previous paleocurrent analyses provided by McKnight (1964), on the one hand, and by Wilkinson and Oles (1968), Jarman (1973), and Kleinhans et al. (1984) on the other. This discrepancy is noted by Kleinhans et al. (1984) who offer as possible explanations: 1) the interplay of obliquely oriented continental slope and basin axis gradients, 2) variations in fan morphology and thus sediment dispersal patterns, 3) multiple sediment sources, and 4) combinations of one or all of the previous possibilities.

The primary objective of the present research was to resolve this difference by doing a more systematic and complete paleocurrent analysis. This was accomplished by using a much larger suite of measurements, a wider sampling of outcrops. In addition, the present research used various current indicators such as sole marks [used previously by McKnight (1964) and Kleinhans et al. (1984) but not by either Wilkinson and Oles (1968) or Jarman (1973)] , clast imbrication (used only by Wilkinson and Oles 1968), orientation of elongate plant fragments, and long-grain orientation (microfabric analysis).

MATERIALS AND METHODS

Field Sampling

My study to determine paleocurrent direction in the Hudspeth and Gable Creek rocks was conducted over three field seasons: fall of 1983, summer and fall of 1984, and spring of 1985. Samples for microfabric analysis were also collected at this time. Although actual field work was conducted for a lengthy period of time, an even wider familiarity with the regional geologic setting was gained during an extended stay in the area while I was well-site geologist on the Steele Energy Donnelly Dome (Keys 1-28) wildcat well drilled just north of the Mitchell Inlier.

During this study I attempted to revisit the sites used by McKnight (1964) in his paleocurrent analysis. However, due to problems with landowners not allowing access and the weathering of outcrops over the past twenty years, I was unable to duplicate his orientation measurements. As neither Wilkinson and Oles (1968) nor Jarman (1973) provided the locations of outcrops they studied, I was also unable to revisit their sampling sites.

Macrofabric

Since sedimentary current features are located on the bottom of sandstone units, excellent exposures are required. In the Mitchell area, this degree of exposure is generally lacking except for roadcuts and stream channels. Thus, extensive field reconnaissance was necessary to identify outcrops with sandstone ledges which could be dug out to uncover fresh surfaces. When sole markings were found, the exact location was noted, the structures described and photographed, and the orientations recorded. The size of outcrops varied considerably; however, any exposure that contained sole markings was utilized. At a given locality, structures were recorded from every possible bed. No limit was set on the number of readings; sampling stopped only when the orientation was recorded from every structure available in the outcrop.

Orientations were taken using a 360-degree Brunton compass corrected for magnetic declination. Measurement of sole marks in steeply dipping beds was accomplished by rotating the readings back to the horizontal assuming that during structural deformation only simple rotation parallel to the strike of the beds had occurred.

Figure 8. Pebble imbrication in clast-supported conglomerate of the Gable Creek facies exposed in a roadcut approximately 11 miles west of Mitchell along Highway 26. Inferred current direction is from right to left.

Imbrication

Imbrication measurements were made at numerous sites within the channelized conglomerate facies previously referred to as the Gable Creek Formation. At these sites measurements were made only on clast-supported conglomerates shingled one upon the other (Figure 8). A minimum of 100 individual imbrications were measured at each site to ensure a statistically adequate data base.

Microfabric

From the sandstone samples collected in the field, ten were selected to test the orientation of elongate sand grains in comparison with that of sole marks which had been previously measured on the base of the same turbidite bed. These oriented samples were collected from the lowermost portion of each bed and in several instances had sole marks on the bottom of the sample. Standard petrographic thin sections were prepared by taking a horizontal section through the oriented outcrop samples parallel to the bottom of the bed.

The long axis orientations of over 100 individual elongate sand grains per section were first measured manually by inserting the thin sections into a 35mm slide projector and projecting the slide onto graph paper. Orientation measurements of elongate grains with a greater than 2:1 length-width ratio were then plotted directly on graph paper by using the least-projection elongation technique of Dapples and Rominger (1945). Using this manual method, the bearing of all grains measured in each sample were then plotted onto rose diagrams. Later a much more rapid and convenient method was applied using computer-assisted microscopy, the Zeiss Video Plan. This method uses a light probe which can be moved to outline individual elongate grains. The computer then figures the orientation of the long axis and automatically calculates means and standard deviations for the 100+ grains measured in each thin section. As the Zeiss system also creates files of all individual measurements, these data can also be entered into a second computer for further statistical analysis.

Statistical Analysis

Statistical analysis was performed on both microfabric and macrofabric samples from all sites within the study area. The von Mises distribution was selected as the method of analysis based upon its ability to analyze circularly distributed data; see Cheeney (1983) for a review.

Paleocurrent data were ranked into two general classes: bidirectional data which give an axis of transport and unidirectional data which give a vectorial direction of transport. A computer program was designed using the von Mises distribution to analyze both the bi- and unidirectional data for each site. Along with the mean direction of transport, confidence intervals were calculated both to the 95% and 99% levels. The mean transport direction for each site was then calculated using the Baysian method of analysis (DeGoot 1969). This method allows for the integration of different structures into a large population and the calculation of a grand mean direction of transport for each site using all the various current indicators measured. The mean transport direction for each site was then charted as arrows on rose diagrams or on regional paleocurrent maps.

RESULTS AND DISCUSSION

General

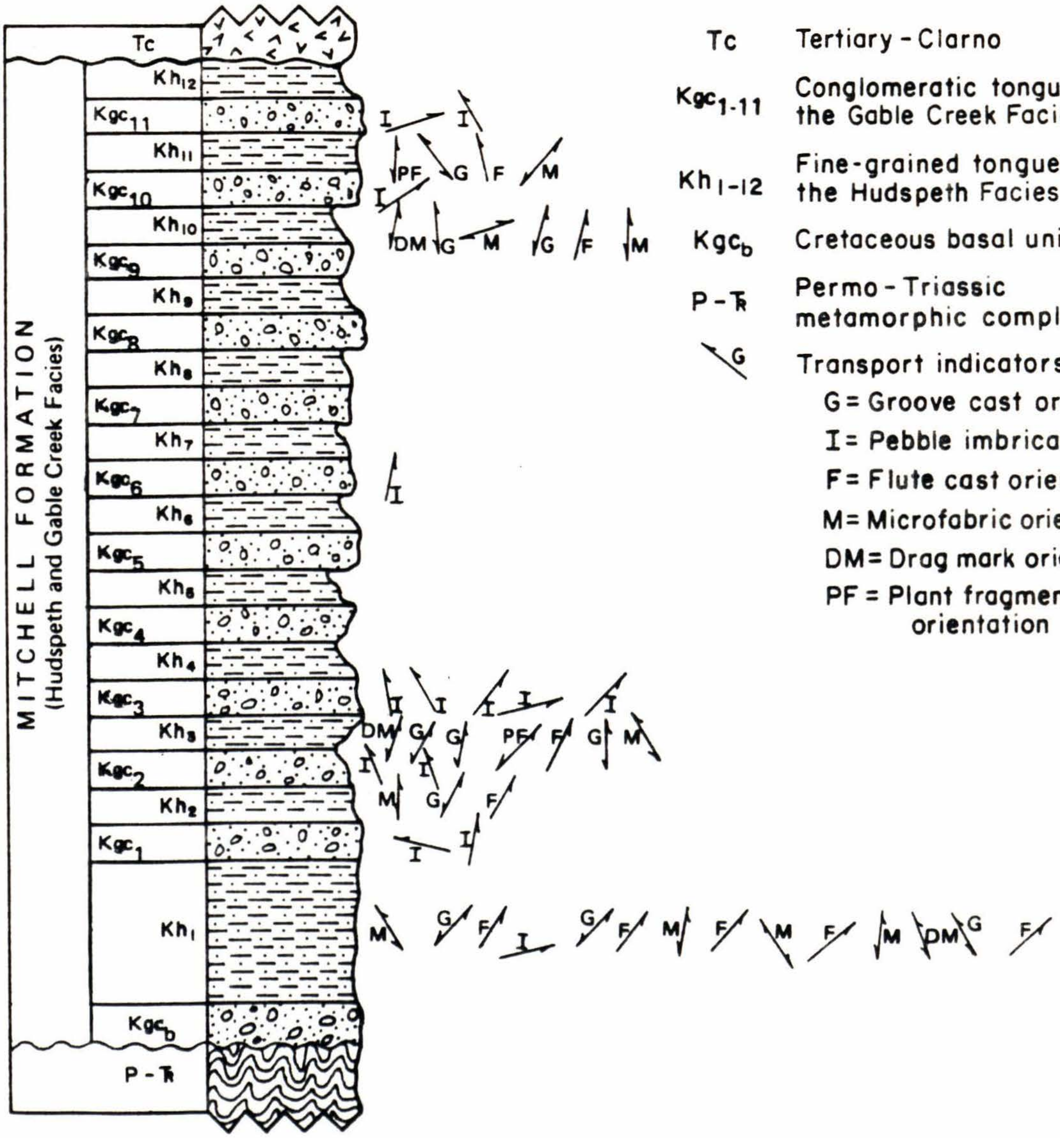
Mitchell Formation outcrops yielded an abundance of sedimentary features useful as paleocurrent indicators including flute casts, groove casts, drag marks, elongate plant fragments, and imbricated conglomerates. Other current features such as ripple marks and crossbedding, although utilized by both Wilkinson and Oles (1968) and Jarman (1973), were uncommon. Kleinhans et al. (1984) have also remarked on the scarcity of crossbedding in the Gable Creek. In agreement with Johnson's (1962) observations, sole marks were commonly observed on the base of 4" to 3' (10 cm - 1m) thick sand-stones but not on those either thicker or thinner. Excellent displays of sole marks can be seen in roadcuts along Highway 26 at locations approximately ten miles west of Mitchell (sites 9 and 12 of this study) and in outcrops on the Old Frizzell Ranch in NWNW section 8, T.11S, R.22E (site 42).

In the field a grand total of 2170 paleocurrent measurements were made of flute casts, groove casts, drag marks, elongate plant fragments, and imbricated pebbles at 29 locations. In addition, 1196 orientations were taken of elongate sand grains in thin sections from ten oriented outcrop samples. The geographic distribution of these sites and samples is given in later paleocurrent maps and exact locations are provided in the Appendix.

The stratigraphic distribution of the sedimentary features used in this study along with their general orientation are shown in Figure 9. Distribution of the data set is strongly bimodal because good outcrops with paleocurrent indicators are rare in the middle portion of the Mitchell Formation.

Figure 10 is a composite rose diagram of all paleocurrent measurements combined into 30-degree arcs. In this diagram unidirectional indicators (flute casts and pebble imbrication) are indicated separately from bidirectional indicators (groove casts, drag marks, plant fragments, and individual sand grains). The grand mean for all 3366 measurements is 25 degrees NNE with a standard deviation of 45 degrees. This rather large standard deviation is largely due to the wide distribution of measurements from the sandstone microfabric (discussed below). Subtracting these 1196 measurements yields a grand mean of 15 degrees NNE and a standard deviation of only 25 degrees. This paleocurrent direction is in remarkably good agreement with that measured by McKnight (1964) but in strong disagreement with the conclusions of Wilkinson and Oles (1968) and Jarman (1973). When the entire data set is divided into individual current features, the reasons for these differences become

Figure 9. Stratigraphic distribution of paleocurrent indicators of Cretaceous rock in the Mitchell area. Subdivision and numbering of tongues follow Wilkinson and Oles (1968).

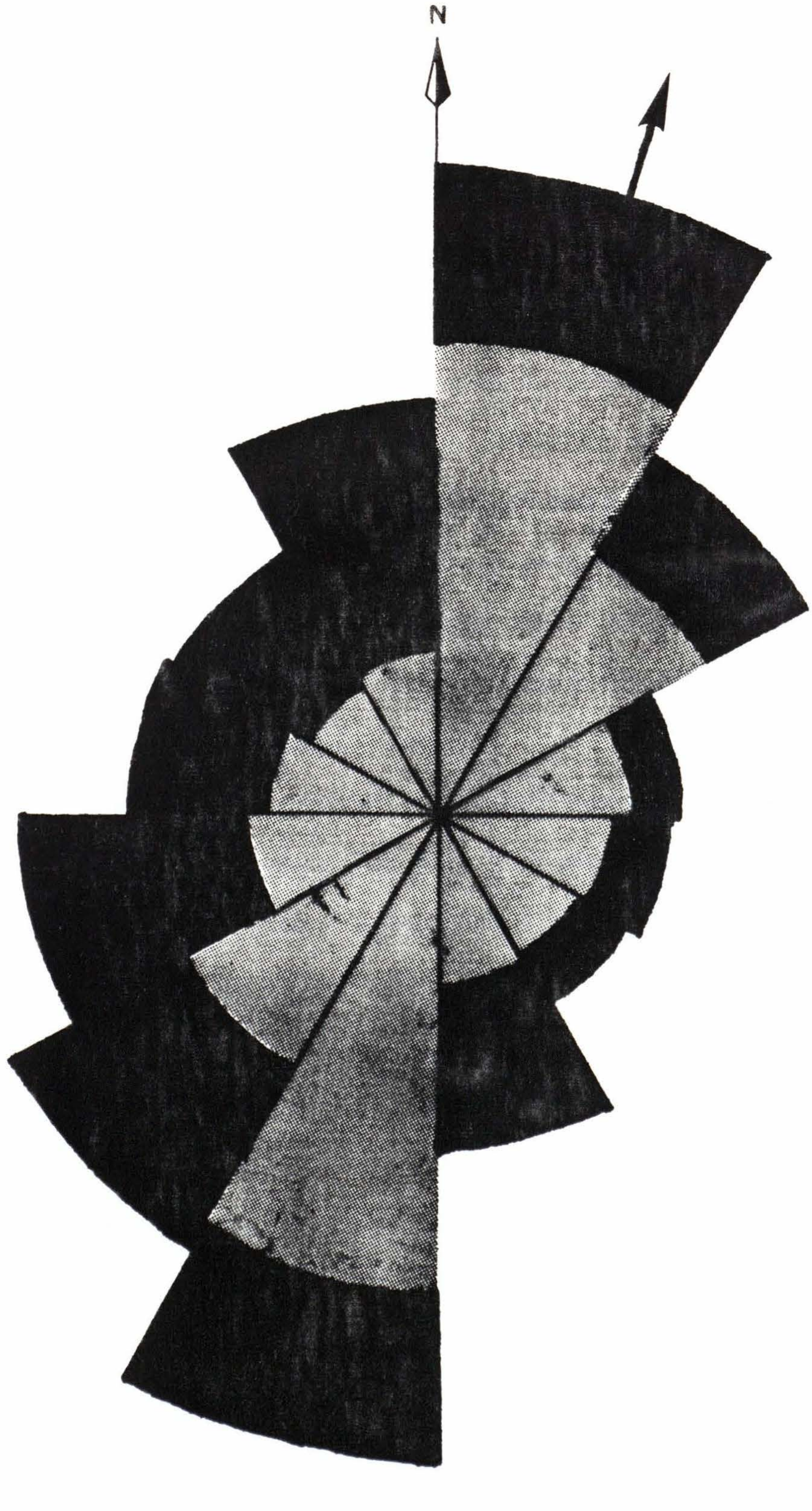


LEGEND

Tc	Tertiary - Clarno
Kgc_{1-11}	Conglomeratic tongues of the Gable Creek Facies
Kh_{1-12}	Fine-grained tongues of the Hudspeth Facies
Kgc_b	Cretaceous basal unit
P - TR	Permo - Triassic metamorphic complex
G	Transport indicators

G = Groove cast orientation
I = Pebble imbrication
F = Flute cast orientation
M = Microfabric orientation
DM = Drag mark orientation
PF = Plant fragment orientation

Figure 10. Composite rose diagram of all paleocurrent orientations measured from the Mitchell Formation. Unidirectional indicators (flute casts and pebble imbrications) are shown in solid black and all others in stippled pattern. The grand mean is shown with a broad arrow.


N

apparent.

Sole Marks

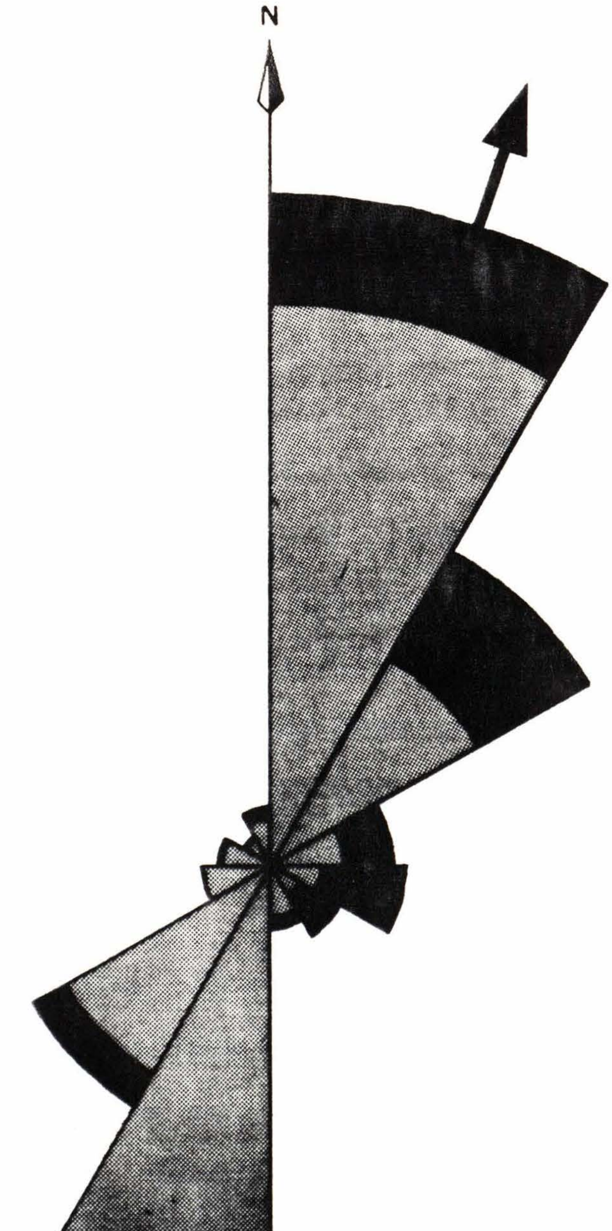
The variety of sole marks found on the base of Mitchell sandstones yielded an abundance of paleocurrent measurements (N=612). Included here are 209 flute casts, 362 groove casts, and 8 drag marks. In this category I am also including 33 orientations of elongated plant fragments found on bedding planes at two sites in close association with sole marks. It is possible that many of the drag marks at these sites were in fact formed by such twigs and/or other transported organic debris.

Of the sole marks discovered and measured, only the flute casts are useful for the purpose of providing actual paleocurrent direction. Groove casts, drag marks, and elongate plant parts provide only bidirectional data. To compute a mean paleocurrent direction for each site, from a mixed population of such uni- and bidirectional data it was necessary to accept the "head" and "tail" of flute casts as giving the general current direction and assume that the bidirectional sole marks agree rather than indicate the opposite paleocurrent direction. Only flute casts with distinct bulbous heads and long tapering tails such as those in Figure 11 were used to determine down-current directions. There were no localities where only bidirectional current

Figure 11. Flute casts with distinct bulbous heads and tapering tails indicating down-current direction to- wards the bottom.


CENTIMETRE
INCH

Figure 12. Composite rose diagram of all sole marks, plus plant fragments from two localities. Flute casts and are indicated in solid black. Grand mean is shown with a broad arrow.

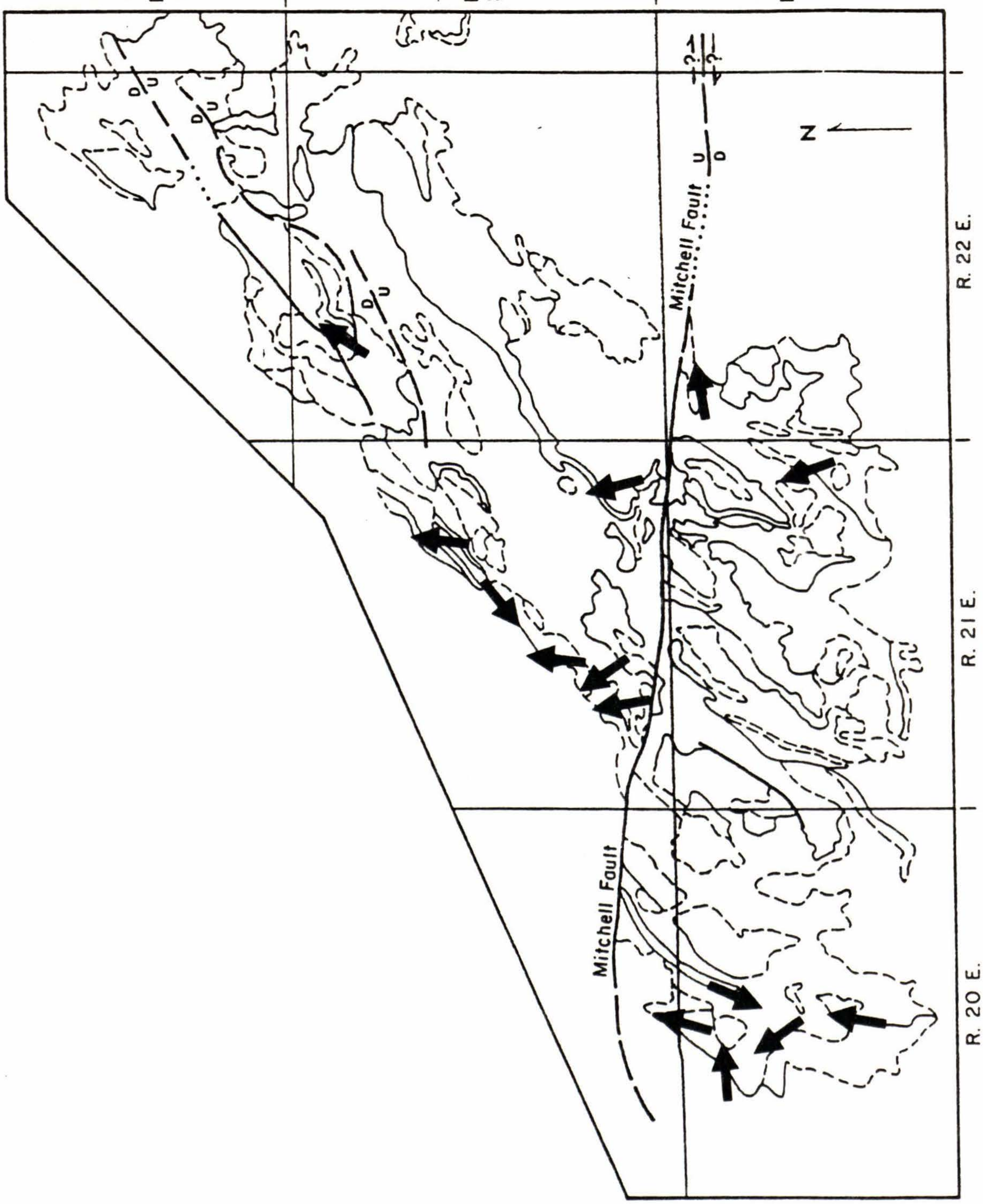

N

indicators were found and thus no cases where an interpretation of one of the two possible directions had to be made independent of flute casts.

A composite rose diagram of the entire population of sole marks (including plant fragments) from 15 sites is presented in Figure 12. In addition, the mean paleocurrent direction indicated by all the sole marks at each individual site is plotted in map form in Figure 13. From these two figures it is quite clear that sole marks provide a fairly consistant indication that the primary paleoslope was inclined toward the north. The few sites with paleocurrent arrows in opposition indicate that a second paleoslope, interpreted to be located on the opposing margin, may have been inclined towards the south. Figure 13 further indicates that the primary sediment transport down the turbidite fan was from the south-southeast toward the north-northwest. However, a subordinate amount of sediment from the opposing margin may have been transported from the north-northwest toward the south-southeast thus influencing the data.

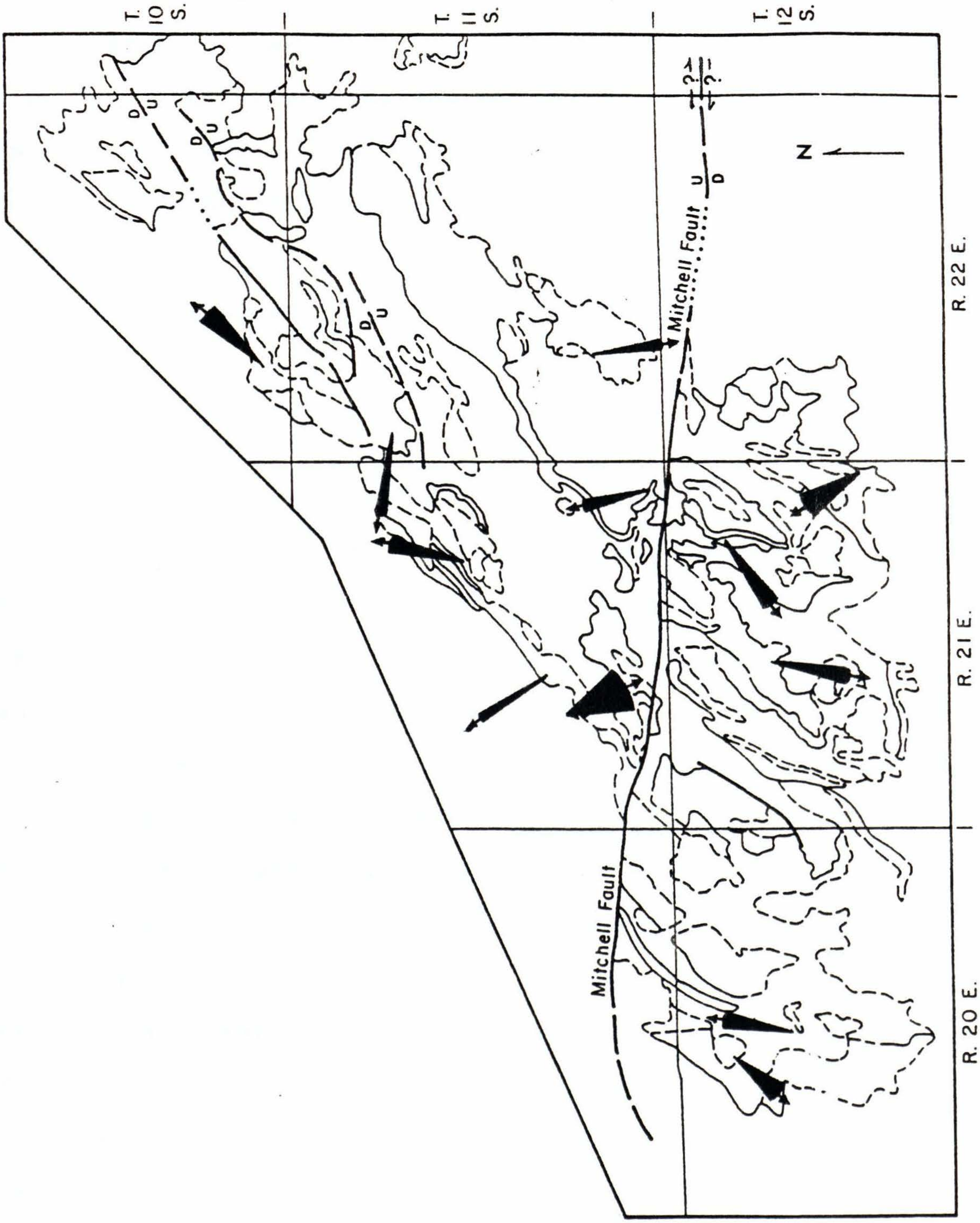
Toward the north and northwest portions of the outcrop area, a discernible trend demonstates sediment transport turned toward the north-northeast, perhaps due to transport along the basin axis into the deeper portion of the basin as interpreted from gravity contours (SEG 1982; Fritts and Fisk 1985b).

Figure 13. Paleocurrent map showing the mean orientations and distribution of sole marks from 15 outcrops in the Mitchell area.


T. 10 S.
T. 11 S.
T. 12 S.
R. 22 E.
R. 21 E.
R. 20 E.
Mitchell Fault
Mitchell Fault
N
U
D

The trend demonstrated by the majority of the measured paleocurrent indicators is in agreement with the paleocurrent direction determined by McKnight (1964) based on a much smaller number of sole marks from 14 locations. However, the subordinate population indicating a southerly current direction is in agreement with the paleocurrent direction proposed by Wilkinson and Oles (1968) and echoed by Jarman (1973). In her abbreviated paleocurrent analysis, Jarman (1973) used cross bedding and ripple marks but specifically excluded sole marks on the basis that, "they are not consistent as directional indicators." This conclusion can be assumed to be the result of either, 1) her own work in which the direction of transport defined by sole marks was unclear because of conflicting current directions, or 2) that Jarman used the results of Wilkinson and Oles' (1968) to conclude that, "they [sole marks] have a range of values from north-south to east-west with no evidence of preferred orientation" (Jarman 1973). Neither statement was supported by paleocurrent data. Moreover, both are in direct contradiction to the conclusions drawn by numerous workers who have routinely used the orientation of sole marks as a key factor in their determination of paleo-transport direction on submarine slopes. Sole markings have become so common as current direction indicators that in their book "Paleocurrents and Basin Analysis" Potter and Pettijohn

Figure 14. Paleocurrent map of conglomerate imbrication from 14 outcrops of the Gable Creek facies of the Mitchell Formation. Arrows indicate the mean direction for over 100 individual readings at each site. Arcs are calculated at 95% confidence intervals.


T. 10 S.
T. 11 S.
T. 12 S.
R. 22 E.
R. 21 E.
R. 20 E.
Mitchell Fault
Mitchell Fault
N
U
D

(1977) stated that "sole markings are the most common and most useful criteria of current direction in flysch facies." From their obvious embrace of sole marks as paleocurrent directional indicators, the prevailing opinion of the practicing geologic community has concluded that sole marks and more specifically flute casts are in fact reliable indicators of paleocurrent direction.

Imbrication

Pebble imbrications within the Gable Creek conglomerate facies were measured at 14 localities and are plotted as mean current directions on Figure 14. The general trend of paleoflow in the Gable Creek facies again appears to have been in a northerly direction. However, a significant number of sites show current flow from the north towards the south in agreement with Wilkinson and Oles (1968), Jarman (1973), and Kleinhans et al. (1984).

In comparing imbrication results to sole mark results it is significant to note that although a visible correlation exists between the two indicators (compare Figures 13 and 14) a number of imbrication sites demonstrate a southerly direction of transport. In some cases this is in direct conflict with solemark orientations obtained nearby. The discrepency between transport indicators is interpreted to be the result of 1) meandering channels on the fan com-

Figure 15. Comparison of microfabric orientations with those measured from sole marks at three sites.

(a) Site 12 illustrates a case where long-grain orientations (microfabric) is in close agreement with sole marks.

(b) Site 14 illustrates a case where microfabric orientation is nearly normal to that of sole marks.

(c) Site 15 illustrates a case where long-grains are randomly oriented while the sole marks show good orientation.

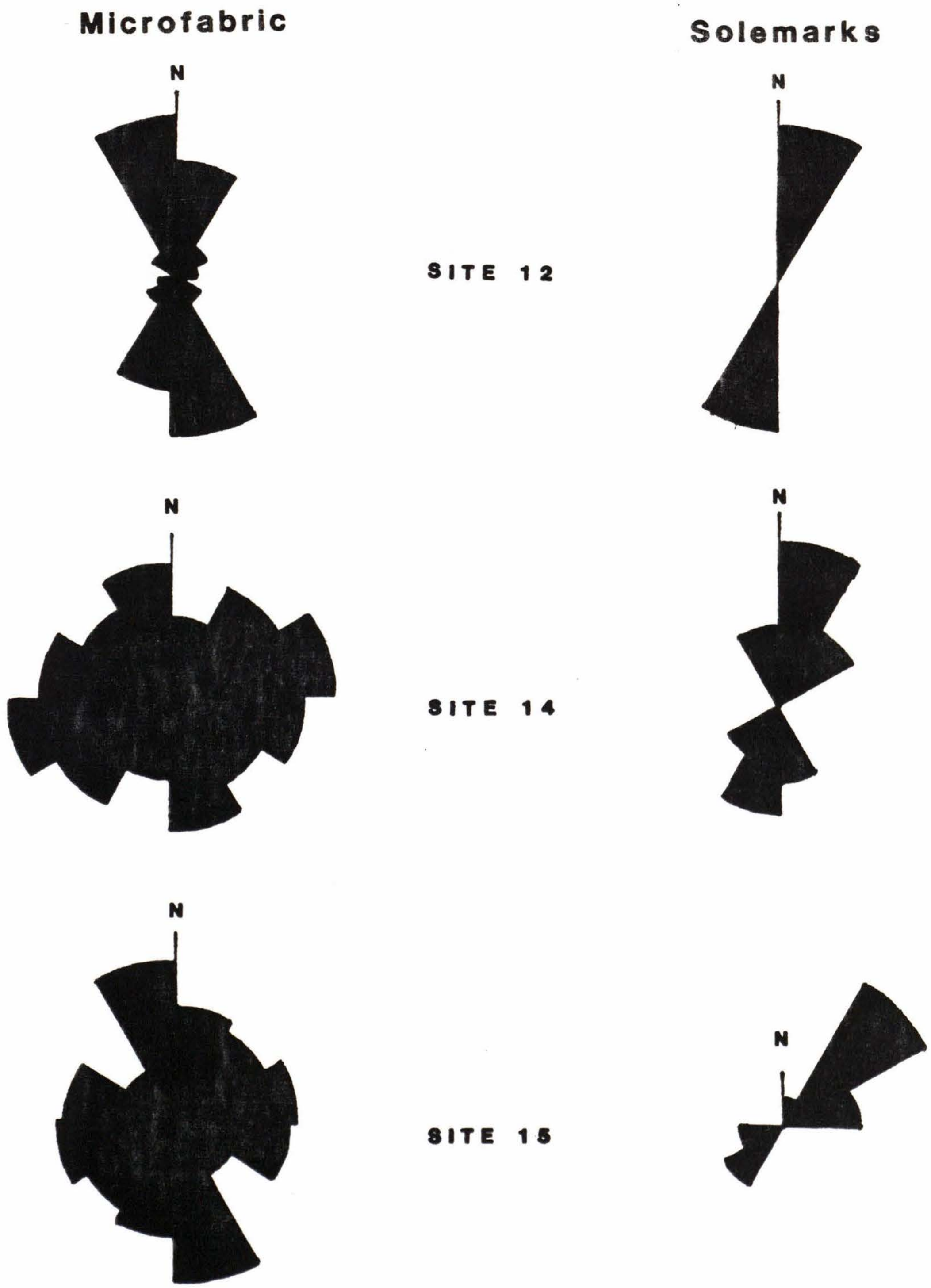

Microfabric
Solemarks
N
SITE 12
N
N
SITE 14
N
N
SITE 15
N

Table 1. Comparison of microfabric orientations with those measured from solemarks at nine sites in the Mitchell Formation.

Site	Microfabric Mean*	Solemark Mean*	Deviation*
12	359	14	15
13	151	84	67
14	3**	21	18
15	32**	55	23
21	6	53	47
26	326	44	78
33	350	41	51
39	359	359	0
42	9	42	33

* In degrees
** Not statistically significant.

plex, or 2) transport of sediment off an opposing basin margin which, although a subordinate population, affects data collected in the area.

Microfabric

A comparison of microfabric orientations to those of sole marks is presented in Table 1. From this comparison three populations of microfabric orientations were observed: 1) fabric in which the preferred grain orientation is in agreement with sole mark orientation at the same site (Figure 15a), 2) fabric orientation in disagreement with sole mark orientation (Figure 15b), and 3) fabric which exhibits no preferred orientation (Figure 15c). The divergence of the mean transport direction for the individual sub-populations vary from a minimum of 0 degrees to a maximum of 78 degrees (Table 1). A statistical summary of all measured deviations indicates that only a portion of the grain orientations (33 percent) fall within 20 degrees of the mean direction of associated sole marks. There is a wide dispersion of deviations from sole markings with no overall tendency for deviations to be clockwise or counterclockwise.

Many workers in microfabric analysis have demonstrated a general trend of alignment of the long axis of grains parallel to the direction of flow as indicated by primary directional indicators (sole markings). See Parkash and Middleton (1970) and Potter and Pettijohn (1977) for excellent reviews. However, there is not a concensus on the usefulness of microfabric in paleocurrent analysis.

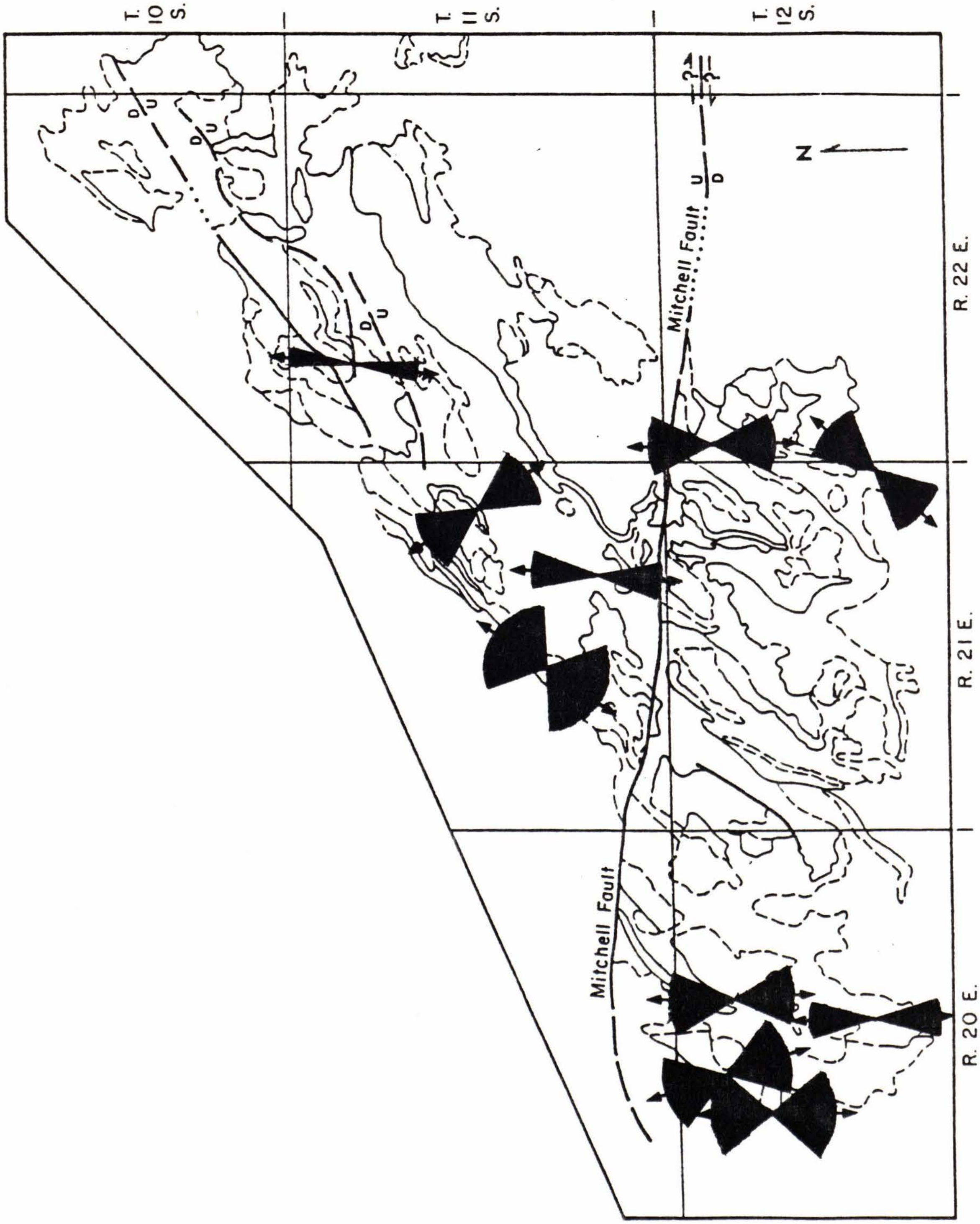
Turbidite fabric analysis has not commonly been done due to the lack of understanding of the hydrodynamics of turbidite flows. The first direct application of grain orientations in a paleocurrent analysis was by Schwartzacher (1951). Smoor (1960, cited by Potter and Pettijohn 1977) reported grain alignment parallel to sole markings. On the other hand, Bouma (1962) did a microfabric study in which he found grain orientations to diverge 90 degrees or at right angles to sole markings. Spotts (1964) made an extensive study of California Miocene turbidites and found that grain orientations diverged from 40 to 60 degrees from sole markings and were consistent from bed to bed. In another study Spotts and Weser (1964) studied samples from a single bed in which the grain orientation was divergent 45 degrees from the sole marks present. Sestini and Pranzini (1965) found three variations in alignment between long grain axes and sole marks: 1) parallel to current as indicated by sole marks, 2) between 20 and 40 degrees of either side of the sole marks, and 3) at 90 degrees to the sole marks. More recently Parkash and Middelton (1970) did a systematic study of turbidite fabric and found grains to generally parallel sole structures.

consistent deviation from sole marks, I agree with Onions and Middleton (1968) that "it is more probable that in some turbidites there is a much higher degree of grain orientation consistency than in other turbidites. The reason for this is at present unknown".

The possibility that the microfabric might be secondary (diastrophic) is highly remote because: 1) there were no visible signs of shearing or metamorphism in either outcrop or thin sections, and 2) in beds showing both flute and groove casts there is good evidence that the fabric is primary. Thus it would seem to be simpler to explain the deviations reported in this study in terms of variations in depositional currents or disturbance of the bed soon after deposition rather than in terms of tectonic reorientation.

Because of the inexplicable deviations of the grain orientations from those of associated sole marks, I have elected not to use microfabric as part of the data set used to draw conclusions on the paleocurrent directions at individual sites. However, a paleocurrent map (Figure 16) has been provided to allow comparison of microfabric with other paleocurrent directions. Although microfabric orientations are not consistent with those indicated by macrofabric, still Figure 16 shows that microfabric orientations are <u>not</u> in disagreement with a general northerly paleocurrent direction.

Figure 16. Paleocurrent map of long-grain orientations measured from thin-sections from ten sites in the Mitchell Formation.


T. 10 S.
T. 11 S.
T. 12 S.
R. 20 E.
R. 21 E.
R. 22 E.
Mitchell Fault
Mitchell Fault
N

In summary, different workers have noted a wide variation in the relationship between grain orientation and sole structures for turbidites. Grain parallelism with associated sole structures has been reported by Kopstein (1954), Ten Haaf (1959, cited by Potter and Pettijohn 1977), Smoor (1960), McIver (1961, as cited by Parkash and Middleton 1970), McBride (1962), Potter and Mast (1963), Scott (1966), and Parkash and Middleton (1970). Grain orientations which deviated from sole marks have been reported by Bassett and Walton (1960), Bouma (1962), Spotts (1964), Spotts and Weser (1964), and Ballance (1964). Evidence for both "parallel" and "normal" orientations within the same bed are reported by Hand (1961), Stanley (1963), and Rukavina (1965, as cited by Parkash and Middleton 1970). Workers such as Onions and Middleton (1968) and Colburn (1968), observed only a slight tendency for "parallelism" of grains to sole structures, and that deviation from the transport direction of macrofabric indicators was very irregular. Although the above is not intended to be an exhaustive review, it is quite apparent that a consensus on the accuracy of microfabric analysis as a technique for defining paleotransport direction is not currently available.

The cause of grain orientation variability in the Cretaceous of north-central Oregon is unknown. Although many other workers have demonstrated good agreement with or a

CONCLUSIONS

From the paleocurrent indicators studied in this analysis, it seems clear that the Cretaceous paleoslope in the Mitchell area dipped predominantly northward, not southward as previously concluded by Wilkinson and Oles (1968). This conclusion is strengthened by the number and variety of sedimentary structures and fabrics used and by the close conformity of their trends throughout the study area. The addition of McKnight's (1964) paleocurrent measurements lends independent support (see Figure 17).

The general current flow direction indicated by flute casts and conglomerate imbrication is normal to the basin margin inferred from gravity data (Fritts and Fisk 1985a and b) and is consistent with sediment gravity flows down a complex subsea fan (Kleinhans et al. 1984). The clastic sediments forming the turbidite fan complex probably originated in tectonically active crystalline highlands further to the south and east. Periodic rejuvenation of this source area probably triggered rapid influx of sediment into the subsiding basin or trough.

Based upon gravity, photogeologic and Landsat imagery analysis combined with extensive field work, Fritts and Fisk (1985a) proposed that gravity "lows" lying both to the south and northwest of Mitchell represent sediment-filled grabens formed by rifting during the formation of the Colum-

Figure 17. Combined paleocurrent map showing orient- ations measured in this study (wider arrows) with those measured by McKnight (1968; thinner arrows)

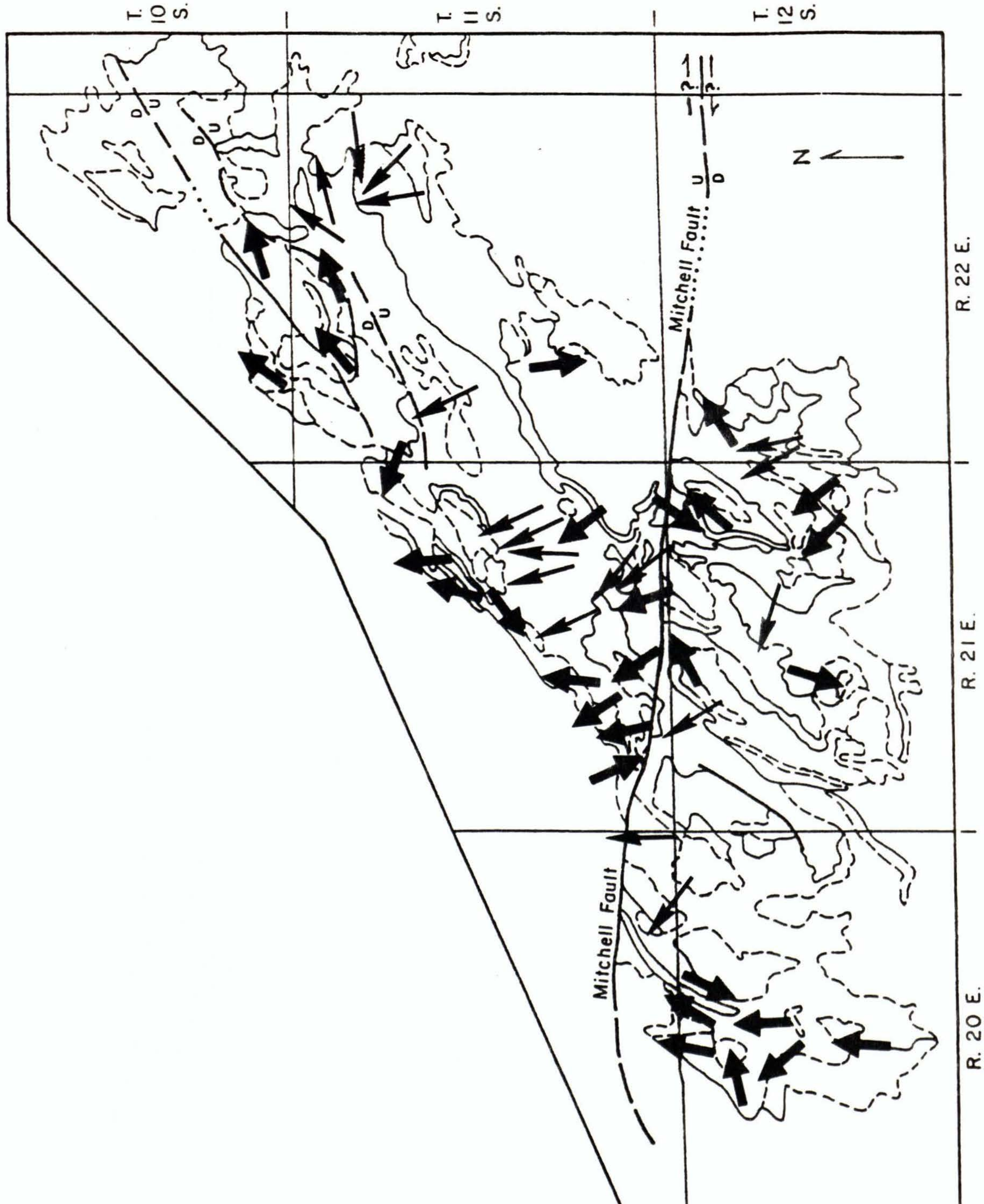
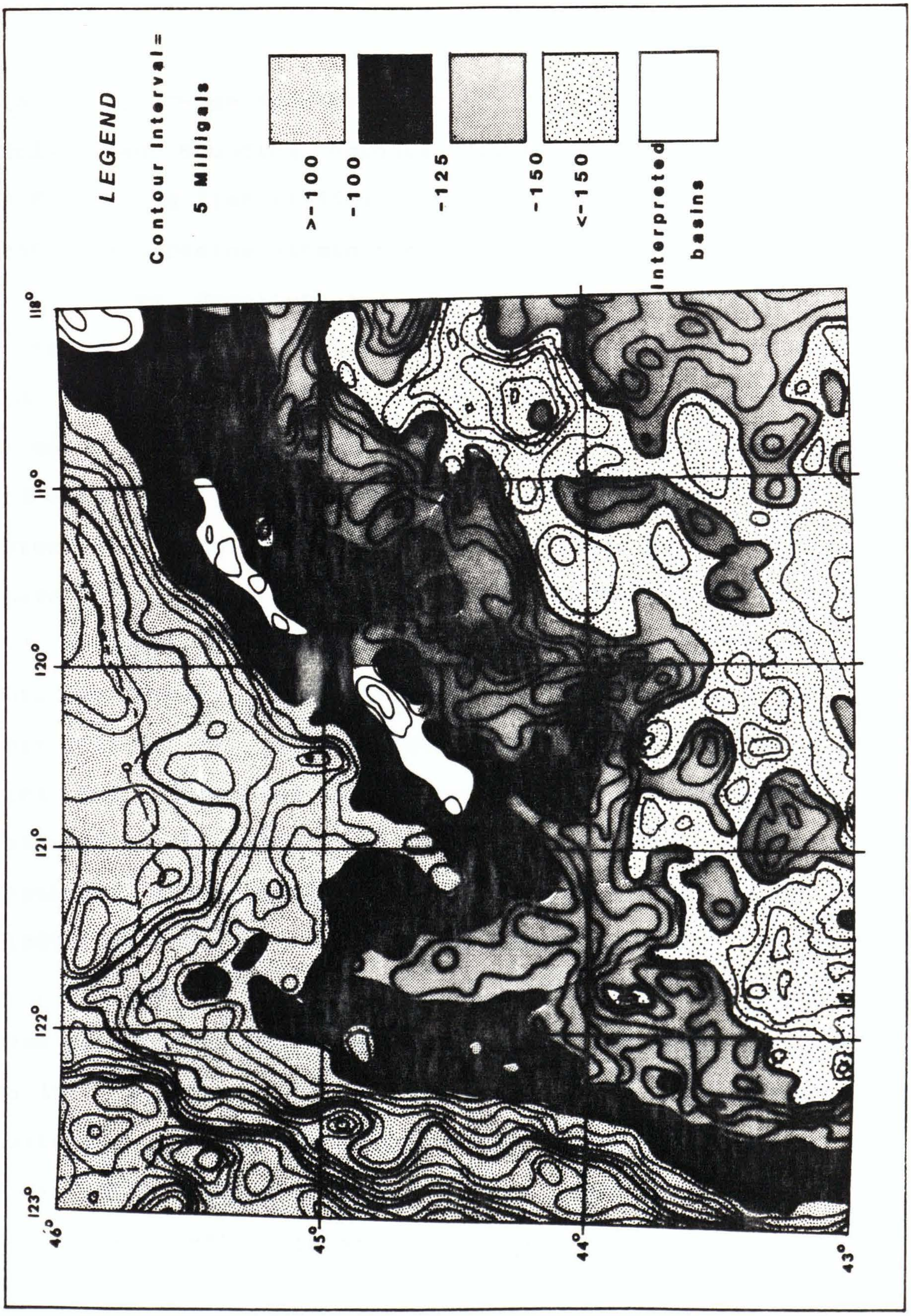

T. 10 S.
T. 11 S.
T. 12 S.
R. 20 E.
R. 21 E.
R. 22 E.
Mitchell Fault
Mitchell Fault
N
U
D

Figure 18. Gravity map of the southern half of the Columbia Basin showing gravity anomalies interpreted to be deep rift-type basins in north-central Oregon. [Modified from Gravity Anomaly Map of the United States, 1982, USGS, Defense Mapping Agency and National Oceanic and Atmospheric Administration.

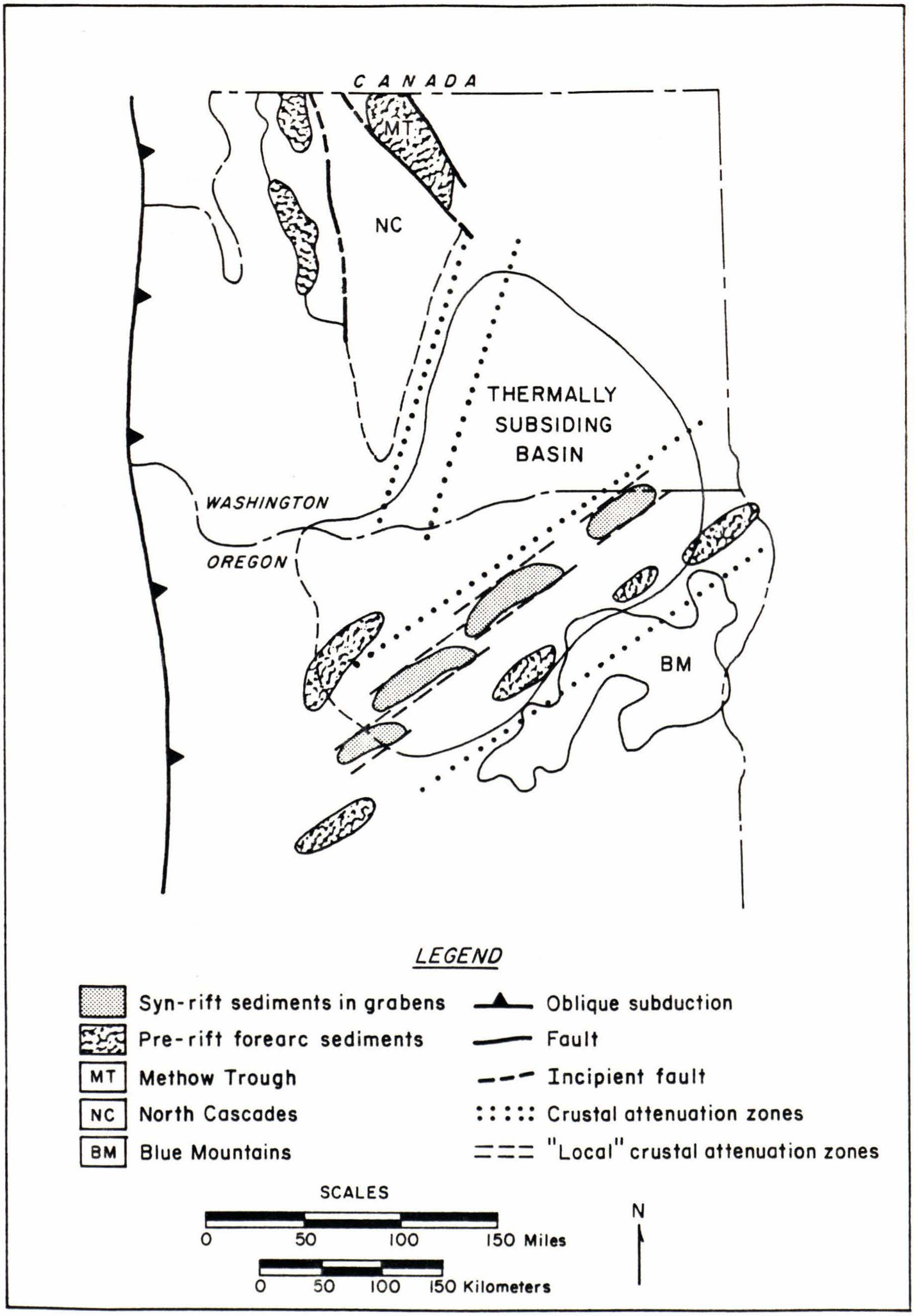

LEGEND
Contour Interval =
5 Milligals
>-100
-100
-125
-150
<-150
Interpreted
basins
118°
119°
120°
121°
122°
123°
46°
45°
44°
43°

bia Basin. These negative gravity anomalies with closed or semi-closed bounding contours (Figure 18) were interpreted by Fritts and Fisk (1985a) to coincide with localized sedimentary sub-basins within the larger rift basin complex.

The development of such sub-basins, according to Fritts and Fisk (1985a) is the expected result of extension and subsidence in the area. Their proposed model is outlined as follows: a) the formation of listric normal faults and associated grabens (sub-basins) as the direct result of extension in the Columbia Basin, followed by b) post-rift phase of regional subsidence of the Columbia Basin (Figure 19). Sedimentation is interpreted by them as occuring during both the faulting and subsidence phases at which time. c) Northwest-facing listric normal faults formed during extension are interpreted to have resulted in the formation of isolated blocks which subsequently were tilted, such as the southeast tilted fault block interpreted by Fritts and Fisk (1985b) as underlying the Mitchell Anticline.

The result of this tectonic activity was the development of isolated basins which were infilled with Cretaceous marine sediments and which are today manifested by northeast-trending negative gravity anomalies (Fritts and Fisk 1985b). On the basis of their tectonic model, Fritts and Fisk (1985b) interpret northeast trending negative gravity anomalies to coincide with graben and half-grabens

Figure 19. Tectonic setting for the development of localized rift-type basins in north-central Oregon. [Modified from Fritts and Fisk(1985a).]



CANADA
MT
NC
THERMALLY SUBSIDING BASIN
WASHINGTON
OREGON
BM
LEGEND
Syn-rift sediments in grabens
Pre-rift forearc sediments
MT Methow Trough
NC North Cascades
BM Blue Mountains
Oblique subduction
Fault
Incipient fault
Crustal attenuation zones
"Local" crustal attenuation zones
SCALES
0 50 100 150 Miles
0 50 100 150 Kilometers
N

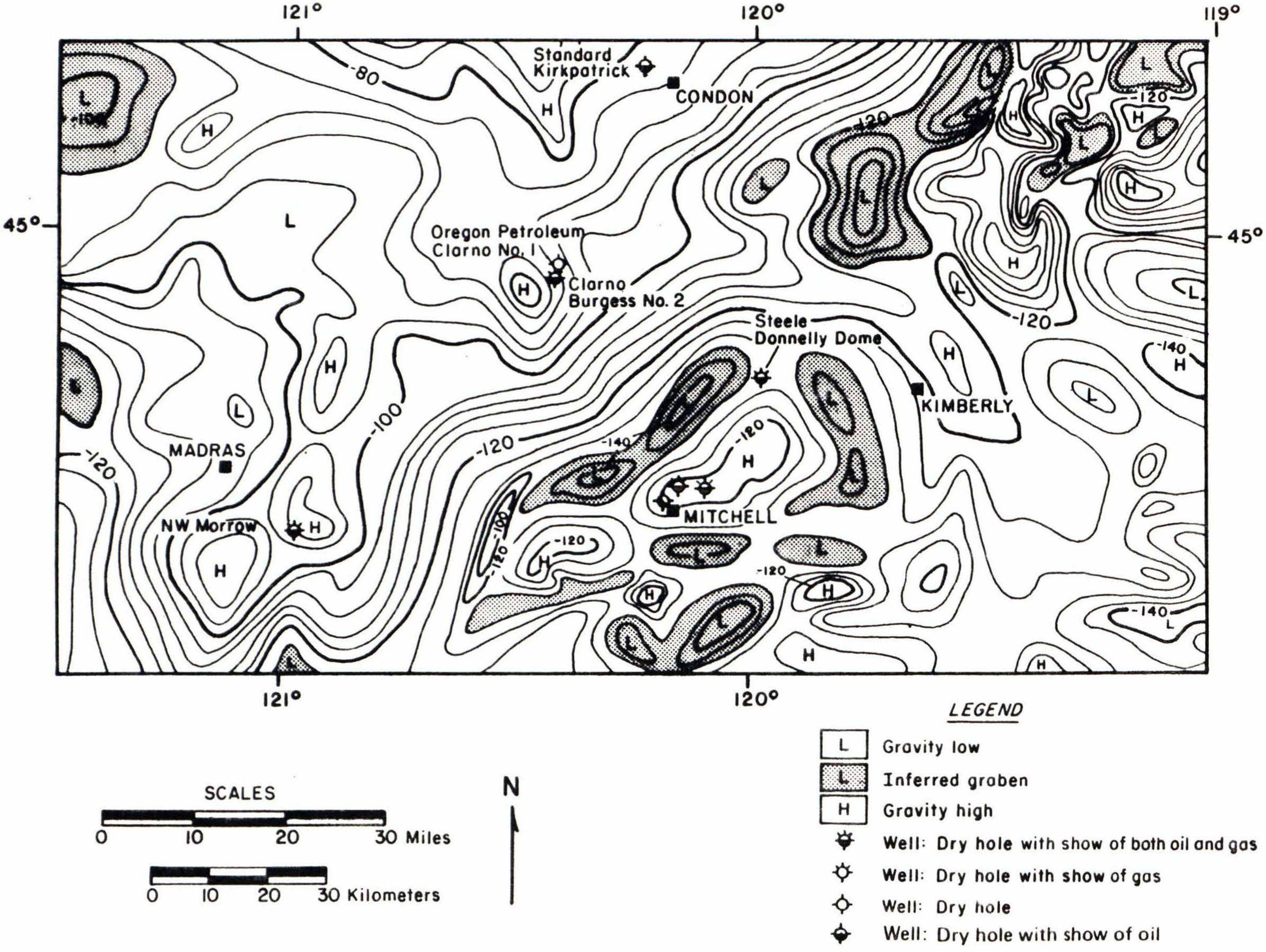
systems with fill of predominately Cretaceous age.

The scenario I believe to have transpired during the Cretaceous time is as follows. Significant extension occurred in the southern portion of the Columbia Basin. At the same time grabens formed and consequently were infilled with sediments. These sediments, the Hudspeth and Gable Creek facies of the Mitchell Formation, were transported through submarine canyons onto paleoslopes. The steepest paleoslopes were, due to the geometry of rift basins, located along the south-eastern margin of the basins. Thus, the majority of the sediments would influx into these basins from the south and east with comparatively minor amounts influxing from the north and west.

The discrepencies in previous studies appear to be the direct result of limited sample size such that the number of outcrops sampled was not sufficent to delineate the true direction of paleocurrent flow. Wilkinson and Oles (1968) and Jarman (1973) lacked the broad data base of paleocurrent indicators necessary to define the true character of this particular sediment dispersal system. In addition, they lacked the recent turbidite fan model of Kleinhans et al. (1984) and the tectonic model proposed by Fritts and Fisk (1985 a and b) for Cretaceous deposition in north-central Oregon to aid them in their interpretations.

The paleocurrent data provided by my study, inconjunction with the restricted rift-basin model proposed by

Figure 20. Gravity map of the Mitchell area (from Fritts and Fisk 1985b).


121°
120°
119°
45°
45°
Standard Kirkpatrick
CONDON
-80
H
L
-120
Oregon Petroleum Clarno No. 1
Clarno Burgess No. 2
Steele Donnelly Dome
KIMBERLY
-100
-120
-140
MADRAS
MITCHELL
NW Morrow
121°
120°
LEGEND
Gravity low
Inferred graben
Gravity high
Well: Dry hole with show of both oil and gas
Well: Dry hole with show of gas
Well: Dry hole
Well: Dry hole with show of oil
SCALES
0 10 20 30 Miles
0 10 20 30 Kilometers
N

Fritts and Fisk (1985b), indicate that the greatest petroleum potential for the area is in restricted linear regions of gravity lows which correspond to thick sediment packages deposited in elongate basins. From information supplied by Fritts and Fisk (1985b) of contoured publically available gravity data (see Figure 20) the Mitchell area is located upon a gravity high. This corresponds to the relatively thin sediment veneer overlying the Permo-Triassic metamorphic complex and is thought to be due to extensive breaching of the Mitchell Anticline. However, surrounding this high, gravity lows almost encircle the area. Therefore, the greatest petroleum potential is not in the immediate Mitchell area, but in adjacent regions which directly correspond to the linear gravity lows. The key point is that the areas thought to have thick sediment sequences are restricted in extent. Thus, petroleum exploration in the region should be conducted in such a manner that would directly correspond to both the gravity lows and structural complexities inherent to the region.

APPENDIX.

Location of sites at which paleocurrent measurements were made.

SITE	LOCATION			
	T.	R.	SECT.	
8	10S.	22E.	SE.NW.	32
9	12S.	20E.	NE.SE.	3
10	12S.	20E.	NE.SE.	3
11	11S.	21E.	SW.SW.	33
12	12S.	20E.	NE.SW.	21
13	12S.	20E.	SW.SE.	4
14	12S.	20E.	SE.SW.	4
15	11S.	21E.	NW.NE.	28
16	11S.	21E.	NW.SE.	36
17	11S.	21E.	NW.NE.	28
18	11S.	21E.	SE.SW.	21
21	11S.	21E.	SE.NW.	26
25	11S.	21E.	SW.NE.	14
26	11S.	21E.	SW.SE.	14
30	12S.	21E.	NE.NE.	11
31	12S.	21E.	SE.SE.	29
33	12S.	21E.	NE.NE.	24
39	12S.	22E.	SW.NE.	6
42	11S.	22E.	NW.NW.	8

APPENDIX. CONT.

SITE	LOCATION			
	T.	R.	SECT.	
43	11S.	22E.	SE.SW.	7
45	11S.	22E.	NE.SW.	7
46	11S.	22E.	SW.SW.	7
48	10S.	22E.	SE.SE.	34
49	10S.	22E.	NW.SE.	34
50	11S.	22E.	NW.NE.	32

APPENDIX. CONT.

Microfabric Location

SITE	LOCATION		
	T.	R.	Sect.
10	12S.	R20E.	NE.SE. 3
12	12S.	R20E.	NE.SW.21
13	12S.	R20E.	SW.SE. 4
14	12S.	R20E.	SE.SW. 4
15	11S.	R21E.	NW.NE.28
21	11S.	R21E.	NW.SW.26
26	11S.	R21E.	SW.SE.14
33	12S.	R21E.	NE.NE.24
39	12S.	R22E.	NE.SW. 6
42	11S.	R22E.	NW.NW. 8

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